NON-DESTRUCTIVE EXAMINATION OF ROCKET MOTOR COMPONENTS[1]

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ABSTRACT

This paper describes a panoramic imaging system for non-destructive examination within cavities typically found in rocket motors. The system relies on a panoramic annular lens (PAL) to produce a flat annular image of the entire 360 degree surround of the optical axis of the lens. The PAL prototype is mounted on a standard CCD camera so that images may be acquired using a standard commercial frame grabber and processor. The annular images are stored using an 80486 microprocessor running on a standard AT bus under the MS-DOS operating system. Algorithms which linearize the images obtained from the prototype and analyze salient features contained in the images are also described.

INTRODUCTION

Since many of the internal components of rocket motors function at high temperatures and pressures, they must be periodically inspected to avoid catastrophic failures. Boroscopic inspection has had a vast and significant effect on improved diagnostics, however, the limited field of view available with current inspection systems has restricted the extent to which full assessment of flaws and their relationship to the surrounding structure may be made. In an attempt to increase the viewing field, technicians must rely on multiple lenses or flexing of the scope tip, depending on the type of boroscope used. These manipulations potentially result in wear or damage to the scope, increased testing time and damage to the structure itself. In general, only spot views or limited views of the region of concern are available. A need exists to develop a new device capable of safely maximizing the field of view within a rocket motor allowing flaws and the surrounding structure to be fully viewed in focus with no distortion of the image or moving parts.

This paper describes an innovative approach to address this need. It outlines steps being taken to design, build and test a prototype system for panoramic inspection and measurement within cavities using techniques classified under radial metrology.[1] The report includes an introduction to radial metrology, a description of the prototype system currently under development, potential applications for this system, an overview of the image processing techniques developed to aid in visual inspection and qualitative analysis, and directions for future research.

RADIAL METROLOGY

Radial metrology combines standard optical techniques with a panoramic annular lens (PAL) and a computer system. The PAL consists of a single piece of glass with spherical surfaces that produces a flat annular image of the entire 360 degree surround of the optical axis of the lens. As illustrated by the ray diagram contained in Fig. 1, the lens produces a virtual image by a combination of reflection and refraction. Since the annular image is formed within the PAL itself, it must be transferred to an image capturing device using a collector lens. The most outstanding attributes of the overall system are that there are no moving parts, the area surrounding the lens can be viewed simultaneously, and the depth of focus extends from the surface of the PAL to infinity.

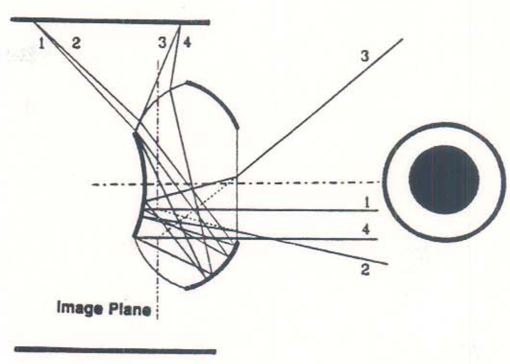

Figure 1. A ray diagram for the panoramic annular lens (PAL).

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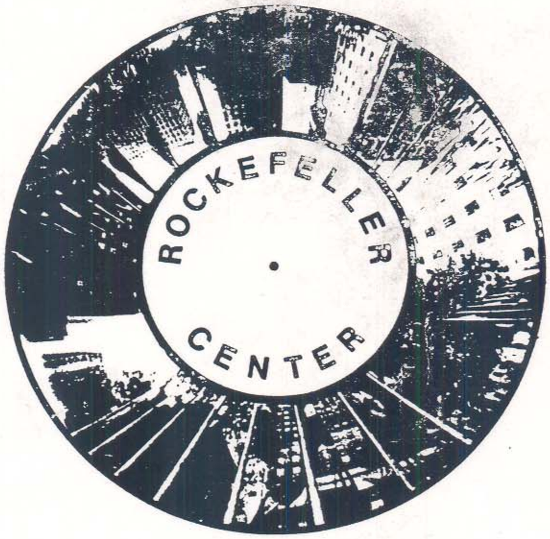

Figure 2. A photograph of Rockefeller Center taken by pointing a PAL camera toward the sky.

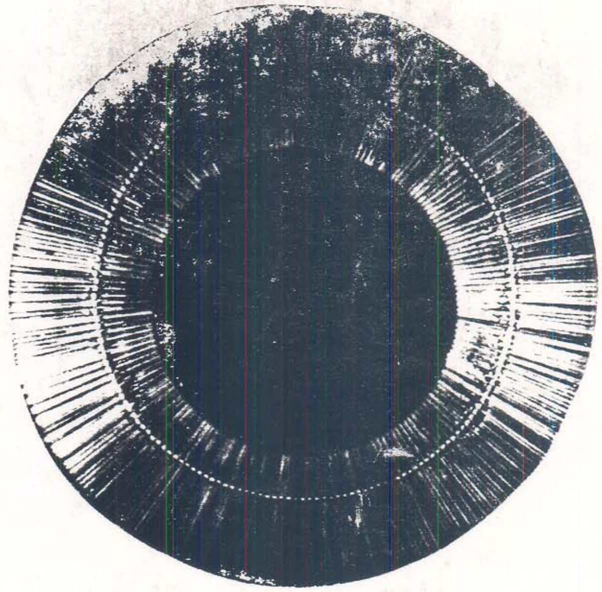

Figure 3. A PAL photograph taken inside the nozzle of an RL-10 rocket engine.

POTENTIAL APPLICATIONS

Figure 2 is a photograph taken in Rockefeller Center with a PAL camera pointed toward the sky and shows the type of imaging that occurs. The tops of the buildings are imaged toward the center of the annular image while the ground appears along the circumference. The photograph demonstrates that extensive information concerning a structure and its position relative to its surroundings may be captured in a single annular image. This feature is illustrated in Fig. 3 which shows a PAL photograph taken inside the nozzle of an RL10 engine. Built by Pratt & Whitney, the RL10 has earned its reputation as the United States' most reliable upper-stage engine and has been responsible for launching numerous satellites and spaceprobes on a variety of earth orbital and interplanetary missions.

Images such as that shown in Fig. 3 can be used as a basis to identify surface or near-surface cracks in weldments, identify seams and foldovers in castings, monitor wear, and detect structural failures. One important application is the visual inspection of the Main Combustion Chamber (MCC) throat of the Space Shuttle Main Engine (SSME). This is required during manufacture, after each test firing, and as part of refurbishment between missions. The temperature is hottest in this region and periodic inspections are performed in an attempt to detect crack initiation, to monitor crack growth, and to observe surface roughness. Current inspection techniques require an inspector to insert his/her head into the throat and visually examine the nozzle contour. Cracks must be at least 3.0 inches or longer before they are recorded on a map of the MCC. The application of the PAL system will automated inspection and, at the same time, eliminate the hazards associated with using support personnel to physically climb up into the nozzle. Moreover, the PAL system may eliminate the need for disassembling systems for inspection of their internal components, thereby saving time and money. A series of tests is scheduled on the Shuttle C Mock-Up to explore these possibilities, the results of which will be reported in a future paper.

PROTOTYPE DEVELOPMENT

The prototype system currently under development captures a cylindrical view of a cavity through the compound lens system shown in Fig. 4. The system includes a 38 mm-diameter PAL and an f/1.4, 25 mm focal length collector lens. The field of view extends from about -20 degrees behind the lens to about 25 degrees in front of the lens; optics are packaged with a standard "C" mount so that the system can be attached to a standard video camera.

An optical system for visual observation and measurement within a rocket motor requires more than a lens; problems associated with illumination of the interior are being addressed. Prior research has shown

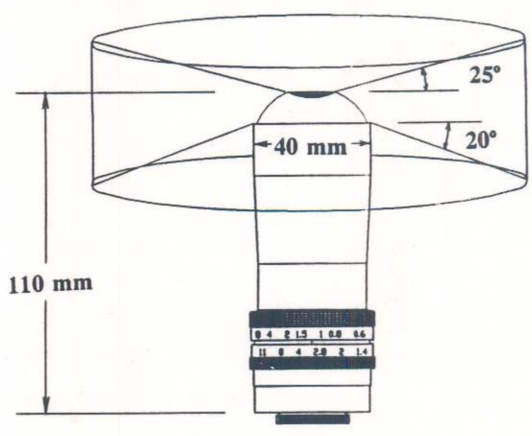

Figure 4. The dimensions and field of view of a 38 mm diameter PAL imaging system. Figure provided courtesy of Optechnology, Inc., Gurley, AL.

that the illumination can be produced by surrounding the PAL system by a number of incandescent bulbs mounted and wired onto an aluminum ring.[2] Problems with this illumination technique arose when using a protective cap for the lens in the system. Glare from the bulbs due to reflections off the cap was pronounced in the panoramic image. Additionally, a uniform illumination of the cavity interior was not achieved. Fear of excess heat generation from the incandescent bulbs was also a factor in exploring alternative means of illumination.

Figure 5. A cylindrical waveguide used to guide light from a remote source to the cavity wall also houses the PAL system.

A more plausible solution to the illumination problem was discovered using waveguide technology. A waveguide is simply a transparent material, such as glass or acrylic, with optically polished parallel sides. Light, directed into one end of the waveguide, propagates and is confined within the waveguide by total internal reflection. Upon reaching the opposite end of the waveguide, the light exits. However, if the waveguide is ground and polished to an angle, such that the incident angle of the light ray is greater than the critical angle as determined by Snell's Law, then the light will reflect completely off the angled portion. This approach is illustrated in Fig. 5 where a cylindrical waveguide is used to transmit light from a remote source to the cavity wall. An added advantage of the waveguide is that it houses the PAL system.

In Fig. 5, the PAL prototype is mounted on a standard CCD camera system having a resolution of 512 x 480 pixels. The hardware platform selected for acquiring and storing images was an 80486 microprocessor running on a standard AT bus under the MS-DOS operating system. Images are acquired by a standard commercial frame grabber and processor and stored in the computer.

PANORAMIC INSPECTION

Besides basic digital image acquisition and data storage, some transformation and numerical analysis of the image may be desirable to simplify visual inspection and quantitative measurement. This is accomplished by computer algorithms which linearize the panoramic images obtained from the prototype and analyze salient features contained in them.

Figure 6, for example, shows a reconstruction of the digital image acquired and stored when the prototype shown in Fig. 5 is positioned along the axis of a cylindrical pipe, the interior surface of which is covered with a test pattern. The test pattern contains a different pattern, *i.e.*, diamonds, squares, checkerboard, and concentric circles, in each quadrant of the cavity wall. The image was photographed directly from a VGA monitor; the information surrounding the image corresponds to the primary data collection screen of a mouse-driven graphic user interface developed to aid in linearizing portions of the image. The user selects four points to define the center and size of the panoramic annular image using the four buttons in the upper left corner. The quadrant to be linearized is selected using the buttons in the lower left corner. The upper right corner displays cursor position and linearization status.

The interface is designed with an emphasis on simplification of use without high graphic overhead. It currently runs on 286/386/486 IBM-PC AT compatible machines with standard VGA graphics requiring at least a 20 megabyte hard drive and a Microsoft compatible mouse. For image capturing, the program uses either a Matrox, Imaging Technology or Cortex frame grabber to produce an image in TIFF format with the 38 mm diameter PAL attached to either a vidicon, CCD or CID video camera.

The linearization program, called PAL^{view}, was developed using Microsoft C. Figure 7 shows the result of applying the program to the fourth quadrant of the image shown in Fig. 6. Two stages of linearization are needed: (1) tangential linearization and (2) radial linearization. In the tangential linearization, a wedge-shaped portion of the annular image of the inside of the pipe is converted into a rectangular section. This is accomplished by 'rolling' the annular image along its outer circumference and moving all the pixels between the contact point and the center of the image to an appropriate location on a vertical line in the final rectangular image. Next, because the annular image is not linear in the radial direction, a vertical stretching of the rectangular image is required; this second process is radial linearization. Details of the process have been reported elsewhere.[3]

PANORAMIC MEASUREMENT

In addition to visual inspection, the PAL system could be used to accurately measure geometrical changes which may occur within a rocket engine's nozzle and combustion chamber. The geometries of these components are critical for optimum performance of the engine. For example, if the geometry of the combustion chamber is not properly maintained, acoustic instabilities may occur as propellants are converted into high-pressure, high-temperature gases. The combustion process may be inhibited should acoustic resonance occur. More importantly, severe damage to the hardware could result. The nozzle is shaped to control the expansion of the exhausting gases so that the thermal energy of combustion is efficiently converted into kinetic energy required to produce thrust. Subtle changes in nozzle geometry may have a detrimental effect on overall

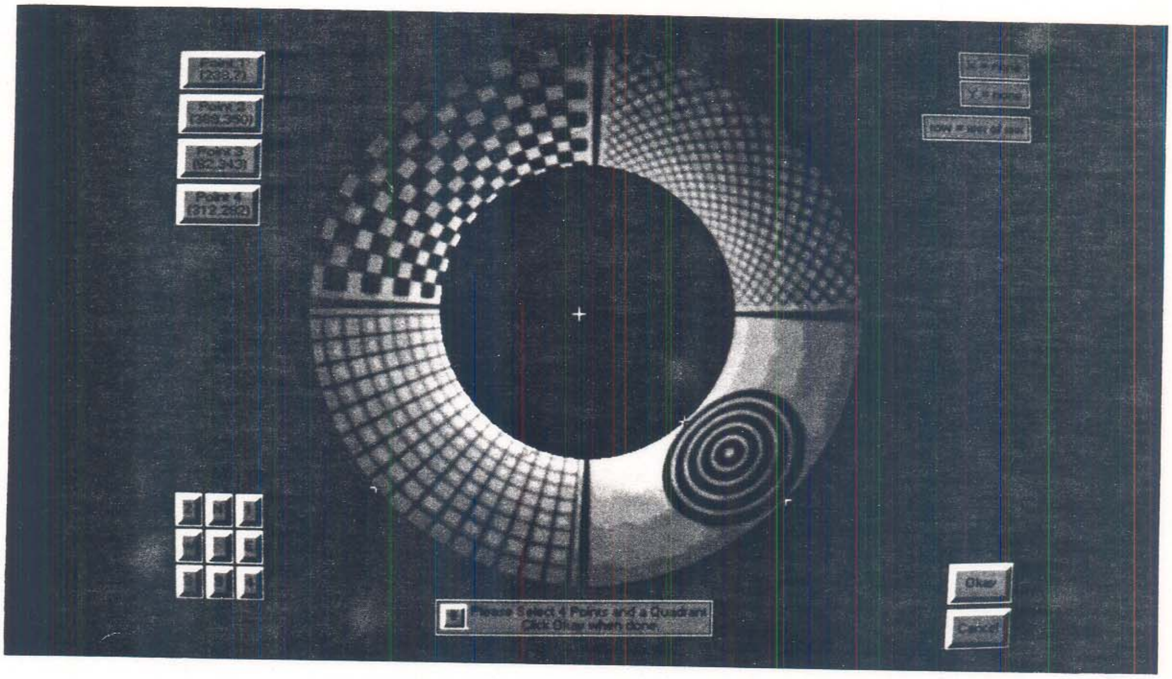

Figure 6. PAL image of a test pattern attached to the wall of a cylindrical pipe. The image is superimposed on the primary data collection screen of a mouse-driven graphic user interface used to aid in linearizing portions of the image.

engine performance.

Contouring may be accomplished by illuminating the cavity wall at an oblique angle using the unexpanded beam produced by a laser diode. Figure 8, for example, illustrates how this approach can be used to visually detect inclusions located on the inner wall of a pipe. In this case, a laser diode and a rotating mirror produce a scan, which was originally circular, that traces out shapes in the annular image which are "similar" to those of the inclusions. PAL^{view} was used to linearize the four quadrants of the image. The lower portion of each trace represents a constant radial distance from the optical axis of the PAL to the wall of the pipe. The shape and dimensions of the inclusions can be easily observed and measured with respect to this baseline using a relatively simple edge finding algorithm. The optical system can be designed so that measurements are based on a linear calibration curve.[4,5]

The entire cavity can be profiled simply by moving the device through the cavity, however, such a procedure limits functional and real-time capabilities. An alternative method for profiling is to digitally record and numerically correlate artificial speckle patterns projected onto the walls of the cavity. In this case, the PAL remains stationary during the measurement and data is taken over the full field of view.

Since the speckle pattern moves as the shape of the cavity changes, the variation in cavity shape can be measured by applying correlation techniques to the speckle patterns obtained before and after the cavity shape is modified. The apparent speckle movement can be computed by numerically correlating small subsets (windows) extracted from each pattern. These shifts can be used to measure surface deflections or to contour the cavity with respect to a reference shape.

In this approach, a number of windows are opened in the first image and moved over the second image to find their best match so that the displacements of each window can be measured.[6] The formula to determine the correlation coefficient, ρ, for a data window taken from

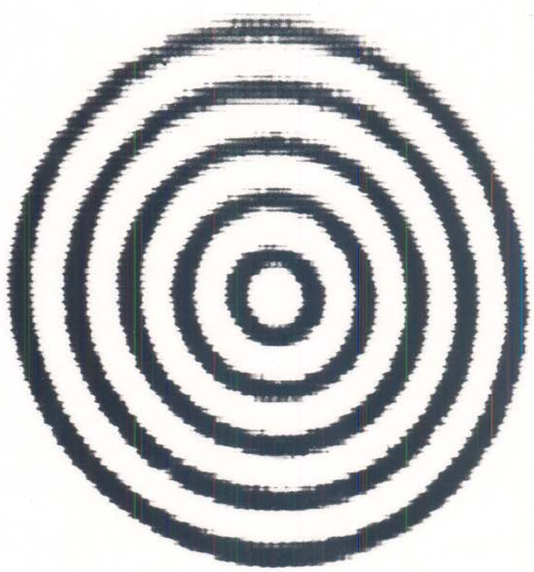

Figure 7. Linearized version of the fourth quadrant of the image shown in Fig. 6.

the first image and centered over location (m,n) in the second image is[7]

$$\rho(m,n) = \frac{\sum_x \sum_Y [f(x,y) - \langle f \rangle][w(x-m,y-n) - \langle w \rangle]}{\{\sum_x \sum_y [f(x,y) - \langle f \rangle]^2 \sum_x \sum_y [w(x-m,y-n) - \langle w \rangle]^2\}^{1/2}} \tag{1}$$

where $w(x,y)$ are the intensity values of the window opened in the initial image, $f(x,y)$ are the intensity values of the second image for those locations under the window values $w(x,y)$, $\langle w \rangle$ is the average intensity values of the window, and $\langle f \rangle$ is the average intensity value of the region located under the window. The maximum correlation value in the search region indicates the best match of the chosen subset (window) from the initial image as located in the second image.

Figure 9 is a schematic of an optical configuration using two opposing collinear PALs which has been evaluated for profiling. A collimated beam of structured light representing a random speckle pattern is introduced into the system at the left and the first PAL projects the speckle pattern onto the walls of the pipe. The second PAL picks up the scattered light and transmits it through a transfer lens to a digitizing camera. The digitizing camera transmits an image similar to the one shown in Fig. 10 to a computer where changes in the image can be recorded and analyzed using digital acquisition and processing techniques. Even though sensitivity varies radially with distance from the center of the lens, calibration procedures for speckle projection have established that families of calibration curves can be expressed in closed form.[8] Feasibility tests have been conducted using this technique to measure deformations inside a cylindrical pipe of constant cross section. In this case, deformation was uniform along the longitudinal axis of the pipe.[9] The more general case, in which the geometry of the cavity and the deformation vary as a function of cavity depth, will be addressed as part of future work.

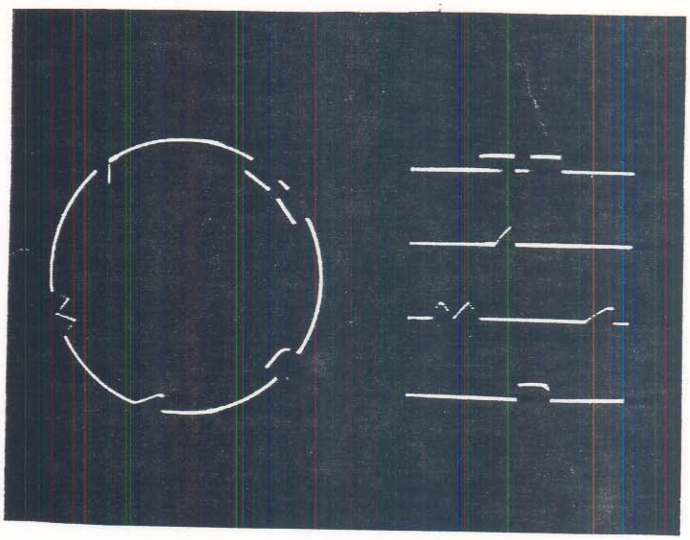

Figure 8. PAL image showing a laser scan over inclusions located on the wall of a cylindrical pipe and the linearized quadrants obtained from PAL[view].

In full-field measurement a number of windows are chosen at locations distributed over the entire initial image to produce a complete contour of the cavity. In measuring displacements, the correlation method must be applied carefully to ensure accurate results. Since digital correlation depends on tracing the motion of speckles projected onto the cavity wall to determine the contour, any window selected in the first image should contain some speckles. Lack of content in a window is one of the reasons which cause spurious results. If a window has no speckles, it is meaningless to find its match in the second image because it does not have any information about the contour. Furthermore, if a window has only one speckle, not enough to make the window unique, correlation methods are likely to find very good matches at several locations in the second image. This will also lead to incorrect conclusions. Structure functions which evaluate the content of a window before the window is selected for use are being developed to obviate these problems. If a window does not meet the requirements of the structure functions, it will be discarded and a neighboring position will be chosen as the new window position and the entire testing process will be repeated. Searching will continue until a satisfactory window is found or every window position has been tried in a predefined region surrounding the original rejected window.

Some PAL images may have a considerable amount of fluctuation in intensity due to background or stray light. This fluctuation, or noise, degrades the quality of the images and impacts strongly on the accuracy of the measurement. This noise often appears as speckles to the correlation algorithm and can spoil the measurement by giving spurious results.

A filter to reduce this noise is being developed based on the assumption that the noise intensity level is very close to that of the background. The approach is to calculate the average pixel value in an image and then set this value as a threshold. Because the speckle intensity values are usually much higher than those of the background and noise, the average intensity value of an entire image will be between the speckle intensity values and noise intensity values so that most noise can be filtered out.

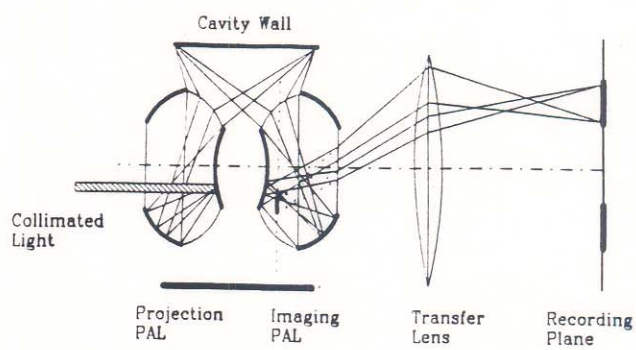

Figure 9. Schematic diagram of a measurement system which relies on two opposing PALs to project and view a speckle pattern on the cavity wall.

Another major problem with the digital correlation method is that it is very time consuming, since a large amount of calculation is needed to evaluate the correlation coefficient ρ. For example, to obtain 121 measurements using windows of 15 by 15 pixels over a search region of 31 by 31 pixels, takes approximately 20 minutes on a 486 microcomputer. By applying two additional algorithms, this time can be reduced to about 5 minutes. One algorithm assumes that the correlation values will not change abruptly between neighboring positions. Therefore, for an area with low correlation values, it is not necessary to evaluate the correlation coefficient at every position, and the correlation calculation may be performed at more widely spaced intervals. The other algorithm uses a modified formula in the correlation calculation to shorten the computation time.

The application of structure functions, filters and time saving algorithms to PAL images is currently under investigation. Further details and results will be reported in a subsequent paper.

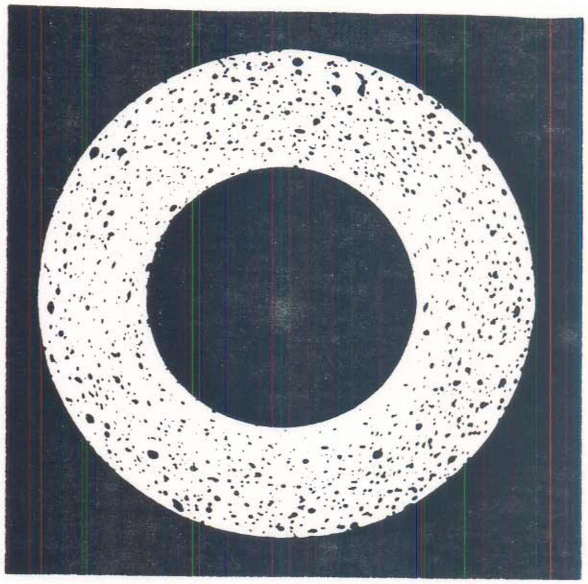

Figure 10. A speckle pattern projected on the cavity wall may be used to contour the region of the cavity contained within the panoramic annular image.

DISCUSSION

In addition to the main combustion chamber which can be examined using the standard 38 mm PAL, there are many other critical components of the SSME located in relatively small cavities that are difficult to reach and inspect. These regions could be examined using a smaller sized PAL. A typical example is the LOX heat exchanger, which contains four tubing welds. Flaws may result from lack of penetration in the original weld, and cracks may be induced in these locations by forming, or by low cycle fatigue during service. In fact, smaller PALs have already been produced and these systems should find widespread applications for nondestructive evaluation of rocket motors. Figure 11, for example, shows a 10 mm diameter probe positioned within a cylindrical pipe that is illuminated externally. Such efforts to miniaturize the PAL and adapt it to a flexible boroscope may ultimately lead to the development of a practical working instrument for inspecting the components of rocket motors through existing ports with minimal inspection effort.

CONCLUSIONS

A new panoramic imaging system has been designed for nondestructive examination of rocket motors. It relies on a unique panoramic annular lens (PAL) which produces a flat annular image of the entire 360 degree surround of its optical axis. The most outstanding attributes of the PAL system are that there are no moving parts, the area surrounding the lens can be viewed simultaneously, and the depth of focus extends from the surface of the PAL to infinity. The annular image may also be linearized for improved human viewing and computationally analyzed to facilitate optical measurement.

PAL systems are currently providing a new inspection capability for the SSME program and can be applied for cavity inspection to verify the condition of space hardware after manufacturing, to perform inservice inspections following ground test engine firings, and to predict potential failure sites during refurbishment between shuttle flights. Current work to evaluate the potential for identifying and locating internal flaws, measuring the depth of surface cracks, comparing design contours to actual part contours, performing automated dimensional inspections, and imaging the relationship of the details in a complex assembly will be of tremendous importance to the space program.

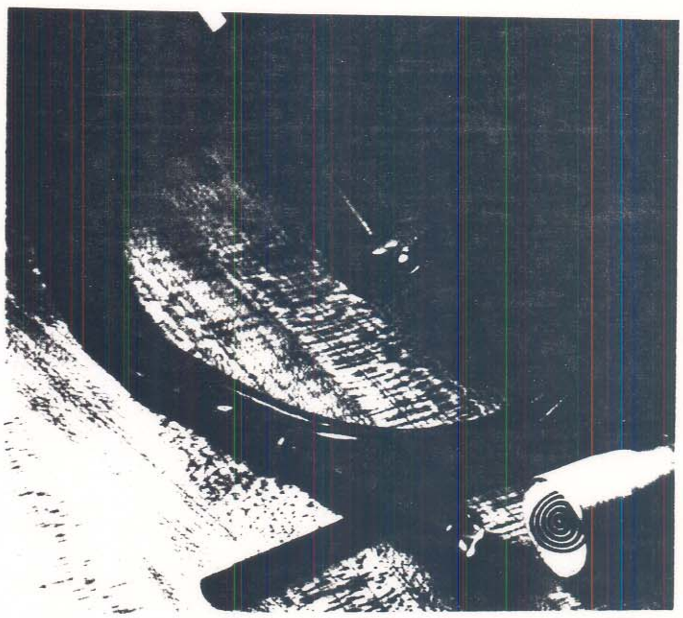

Figure 11. A 10 mm diameter PAL probe positioned within a cylindrical pipe that is illuminated externally.

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